

# PREPARING FOR THE BIG ONE

Swaminathan Krishnan <sup>1</sup>

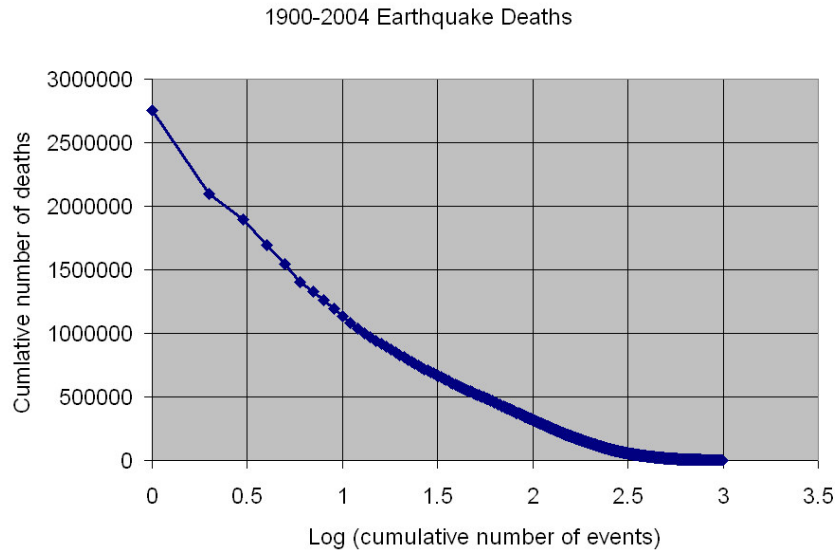
## Introduction

Approximately 2.75 million deaths have occurred in 3000 earthquakes in the last 105 years between 1900 and 2004 (Figure 1A). About one-half of these occurred in the seven deadliest events, i.e., a few events dominate historical death count. These events did not necessarily have large magnitudes, but occurred close to heavily populated regions. If these not-so-large earthquakes could cause such destruction, one can only imagine what would happen if an extreme event were to occur. An extreme event can be defined as one of large magnitude occurring in the proximity of a densely populated region. Extreme events are rare because large magnitude events are rare. Shown in Figure 1B is the Gutenberg-Richter relation for all earthquakes that have occurred between 1904 and 2000 (Kanamori and Brodsky 2001). In these 96 years, fewer than one magnitude 8.0 earthquake has occurred on average each year. Traditionally, civil engineers have adopted an observe, learn, and improve approach for earthquake damage mitigation. Unfortunately, with extreme events being rare, the learning process is slow and, as a result, corrective measures are ineffective. In fact, we have not seen the effects of a large magnitude earthquake occurring close to heavily populated urban regions such as Los Angeles, Seattle, Istanbul, Jakarta, Tokyo, Taipei, Kaosiung, Delhi, Mumbai, Calcutta, Beijing, etc. in recent years. The recent magnitude 6.7, January 17, 1994, Northridge earthquake, the magnitude 6.9, January 17, 1995, Kobe earthquake, the magnitude 7.4, August 17, 1999, Kocaeli earthquake, and the magnitude 7.7, September 21, 1999, ChiChi earthquake have provided us with glimpses of what we can expect from a major earthquake. But the data from magnitude 8 earthquakes in urban settings is quite limited. Although the magnitude 8.0, September 19, 1985, Michoacan earthquake killed 10000 people and caused significant damage in Mexico City, it was centered more than 360 km away from Mexico City. Both the magnitude 9.5, May 22, 1960, Chile and the magnitude 9.2, March 28, 1964, Prince William Sound, Alaska earthquakes occurred close to sparsely populated regions. The magnitude 7.8, July 28, 1976, Great Tangshan earthquake, the magnitude 8.3, September 1, 1923, Great Kanto earthquake, and the magnitude 7.7, April 18, 1906, San Francisco earthquake provide the best clue to what could be expected from a large earthquake close to an urban center. The fires following the 1923 and 1906 earthquakes destroyed the cities of Tokyo and San Francisco, respectively, although quite a bit of damage can be attributed to ground shaking as well. Ninety percent of the buildings in the city of Tangshan were flattened in the 1976 earthquake. Unfortunately, recorded data from these earthquakes is minimal. As a result, if we are to prepare for an extreme earthquake striking one of our major metropolitan centers, we cannot rely solely on the traditional approach of learning from observations.

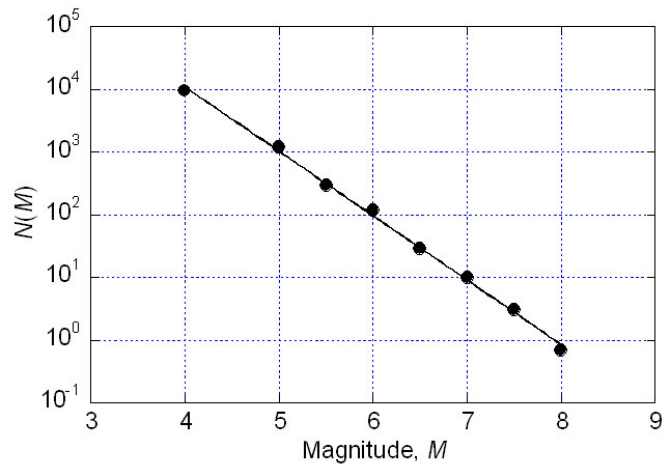
As civil engineers the only alternative left to us is to be proactive at the backend and the frontend of disaster management, instead of being reactive to natural disasters. At the “backend”

---

<sup>1</sup>Seismological Laboratory, MC 252-21, California Institute of Technology, Pasadena, CA 91125, USA.  
Email: krishnan@caltech.edu



A



B

Figure 1: [A] The cumulative number of deaths in the earthquakes that have occurred between 1900–2004 are shown plotted against the logarithm of the cumulative number of events (Source: Professor Thomas H. Heaton, California Institute of Technology). This illustrates that just seven of the three thousand earthquakes account for half of the 2.75 million deaths that have occurred in these earthquakes. [B] The Gutenberg-Richter relation for earthquakes between 1904–2000 illustrates that fewer than one magnitude 8 event occurs globally every year (Source: Professor Hiroo Kanamori, California Institute of Technology).

we have to try to estimate the destructive power of an extreme event, and its effects on the built environment. With these estimates we have to develop improved designs of civil engineering systems and transfer this technology to practice in a timely manner so that “frontend” implementation can be realized prior to the occurrence of an extreme event. In order to quantify the power of an extreme

event, we need to understand the underlying science and incorporate it into the phenomenological modeling of the event. Integrating science into our engineering decision-making may require active interdisciplinary collaboration with seismologists. The field of seismology has undergone a revolution of sorts in the last decade or so, with the advent of parallel computing as a seismological tool. Seismologists have developed numerical tools to propagate seismic waves through the Earth in three dimensions (Komatitsch and Tromp 1999). One can simulate an earthquake by assuming a kinematic source (slip as a function of space and time) on a prescribed fault and compute ground shaking at great distances by numerically propagating the seismic waves through the three-dimensional (3-D) Earth medium. Where, in the past, we would base our estimates of seismic demand on observations from historical earthquakes, now, we can estimate this demand in a far more quantitative manner than was possible before.

The Global Positioning System (GPS) can estimate the rates of strain accumulation on various faults (<http://gsrm.unavco.org>), which can then be used to develop the kinematic source models. Alternately, slip distributions from finite-source inversions of ground motion records from earthquakes on geometrically similar faults in other parts of the world can also be used as the starting point to estimate the effects of similar earthquakes on faults in the region of concern. 3-D modeling of the physical phenomenon of an earthquake includes the effects of directivity, slip distribution, basin amplification, etc. Once the seismic hazard is quantified in this manner, the second part of the backend effort is to then analyze civil engineering systems for this hazard and, based on their performance, develop strategies to improve them.

Frontend implementation of the disaster mitigating strategies developed at the backend faces several challenges, primary among them being ignorance, poverty, corruption, and political will or lack thereof. How we overcome these challenges may very well determine our success in mitigating disasters. In this paper, a few examples of backend and frontend implementation of disaster mitigation strategies being undertaken in various parts of the world are presented. These examples will illustrate possible approaches to prepare for extreme events.

## **Example of a Backend Implementation – San Andreas Earthquake Simulation**

The San Andreas fault is a right-lateral strike-slip fault running along the west coast of the United States that arguably poses the greatest seismic risk to the built environment along the west coast in general and, in particular, the Los Angeles metropolitan region in southern California, and the San Francisco metropolitan region in northern California. In as far as southern California is concerned, historical accounts (Agnew and Sieh 1978; Meltzner and Wald 1998) detail the occurrence of a large earthquake on January 12, 1857, with strong ground shaking having been felt across a vast area of more than 350,000 km<sup>2</sup> (Sieh 1978b). These accounts point to long-period, large-amplitude, long-duration, shaking in the Los Angeles and San Fernando basins. Paleoseismological studies on the San Andreas fault in the last few decades deduced the magnitude of this earthquake to be about 7.9 (Sieh 1978b) with rupture estimated to have initiated at Parkfield in central California and proceeding down south a distance in excess of 360 km. These studies further conclude that such earthquakes could have occurred on the San Andreas fault every 200–300 years (Sieh 1977; Sieh 1978a; Sieh et al. 1989; Weldon et al. 2005). If we want to prepare the heavily

populated engineered environment of southern California for this impending extreme event, we have to start by quantifying the motions expected from an 1857-like earthquake. This can be done numerically using SPECSEM3D (<http://www.geodynamics.org>), a seismic wave propagation program based on the spectral element method (Komatitsch and Tromp 1999). This methodology has been shown to accurately simulate waveforms down to a period of 2 s (Komatitsch et al. 2004; Liu et al. 2004). Shown in Figure 2 is the scope of one such simulation. The inset shows the rupture of a 290 km segment of the San Andreas fault starting at Parkfield and proceeding down south towards the Los Angeles metropolitan area. The inhabited region of interest is comprised of three basins– the San Fernando valley, the San Gabriel valley, and the Los Angeles basin. The cities of Encino, Canoga Park, North Hollywood, Northridge, Chatsworth, etc., are in the San Fernando valley; Alhambra, Baldwin Park, etc., are located in the San Gabriel valley; and the cities of Los Angeles, Beverly Hills, Santa Monica, Compton, etc., are located in the Los Angeles basin. The entire region is divided into 636 analysis sites on a grid spaced at about 3.5 km in the north-south and the east-west directions.

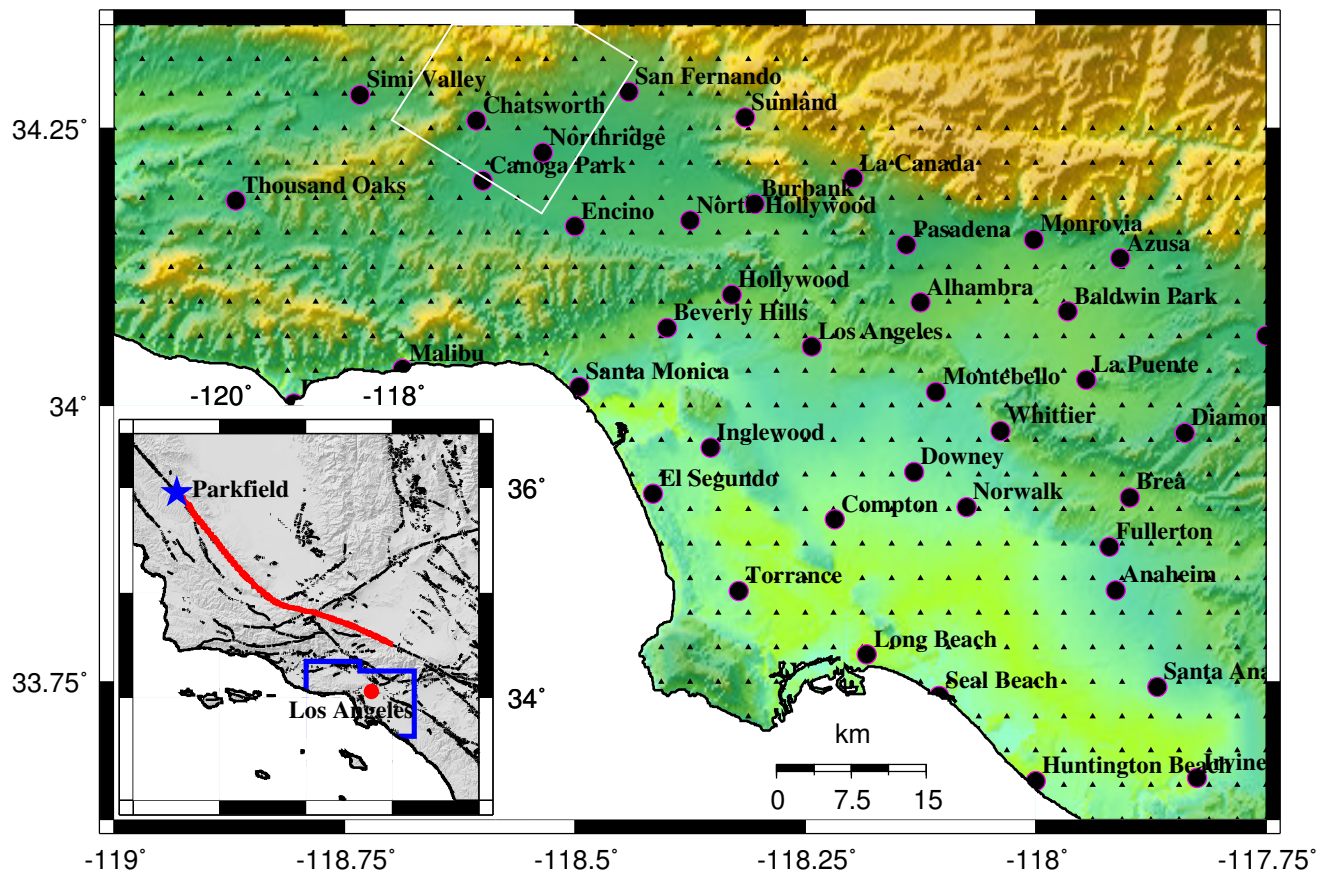


Figure 2: Geographical scope of the simulation (The color scheme reflects topography, with green denoting low elevation and yellow denoting mountains): The solid black triangles represent the 636 sites at which seismograms are computed and buildings are analyzed. The white box is the surface projection of the Northridge fault. The red line in the inset is the surface trace of the hypothetical 290 km rupture of the San Andreas fault that is the primary focus of this study. The area enclosed by the blue polygon denotes the region covered by the 636 sites.

To represent the earthquake source in a realistic manner, a finite-source model of the mag-

nitude 7.9, November 3, 2002, Denali earthquake in Alaska, determined by inverting recorded seismograms, is mapped on to the San Andreas fault with rupture initiating at Parkfield. The Denali fault is geometrically similar to the San Andreas fault and the 2002 earthquake rupturing 290 km of this fault is a good candidate for this simulation which aims at recreating an 1857-like earthquake on the San Andreas fault. The peak slip is about 12 m at depth and about 7.4 m at the surface. The rupture dimensions are 290 km by 20 km. This kinematic source is imposed on the San Andreas fault and three-component ground motion seismograms are computed at the 636 analysis sites using SPECFEM3D. Maps of peak velocities and displacements for the three components of ground motion are shown in Figure 3. In this scenario, peak velocities are of the order of 2 m/s and peak displacements are of the order of 2 m. Peak ground motion varies significantly in the region. Hot-spots are seen even at distances as far as Anaheim and Fullerton. This simulation demonstrates that local geology, propagation path, rupture directivity, and slip distribution have a profound effect on the intensity of ground motion in the region.

With the seismograms at hand it is now possible to estimate the effect of such an earthquake on engineered structures. As an example, a 3-D structural model of an existing 18-story steel moment-frame building in Woodland Hills (Figures 4A and 4C) is placed at each of the 636 analysis sites and is analyzed for the synthetic ground motion computed at each of these sites. The structural analyses are performed using FRAME3D (<http://www.frame3d.caltech.edu>), a nonlinear analysis program that is capable of simulating damage in steel buildings (Krishnan 2003b; Krishnan 2003a; Krishnan and Hall 2006a; Krishnan and Hall 2006b). This building was designed according to the 1982 Uniform Building Code (ICBO 1982) and built in 1986. A significant number of welds in beam-to-column moment connections in this building fractured during the magnitude 6.7, January 17, 1994, Northridge earthquake (SAC 1995). A map of the peak interstory drift ratio computed in the building model under the simulated San Andreas earthquake ground motion is illustrated in Figure 5A. Where peak drifts exceed 0.05, the building can be considered to be severely damaged while peak drifts below 0.007 are indicative of the building being immediately occupiable following the earthquake (FEMA 2000). Peak drifts excess of 0.025 are indicative of life-safety being compromised. This map gives an estimate of the performance of this particular structure when located anywhere in southern California.

The lessons learnt from the Northridge earthquake led to an upgrade of the Uniform Building Code in 1997 (ICBO 1997). The two major modifications impacting the design of buildings such as this are the near-source scaling of the seismic base shear to account for the proximity of faults with large rates of strain accumulation, and the upward scaling of the base shear to account for the lack of redundancy in the lateral force-resisting system, where applicable. For steel moment-frame buildings, redundancy is defined as a function of the number of moment-frame bays. The impact of the building code upgrade on the performance of the 18-story building can be assessed in part by redesigning it according to the new provisions (Figures 4B and 4D) and analyzing it for the ground motion at the 636 analysis sites from the San Andreas earthquake simulation. The map of peak drifts from such an analysis of the redesigned building is shown in Figure 5B. The improved performance of the redesigned building in comparison to the existing building is apparent. Unfortunately, even the redesigned building has damage at many locations warranting closure and significant direct and indirect losses as a result. For example, at Northridge, the existing building model collapses under the San Andreas motions, while the redesigned building has a large permanent offset at the roof that would render the building unusable for a significant period of time



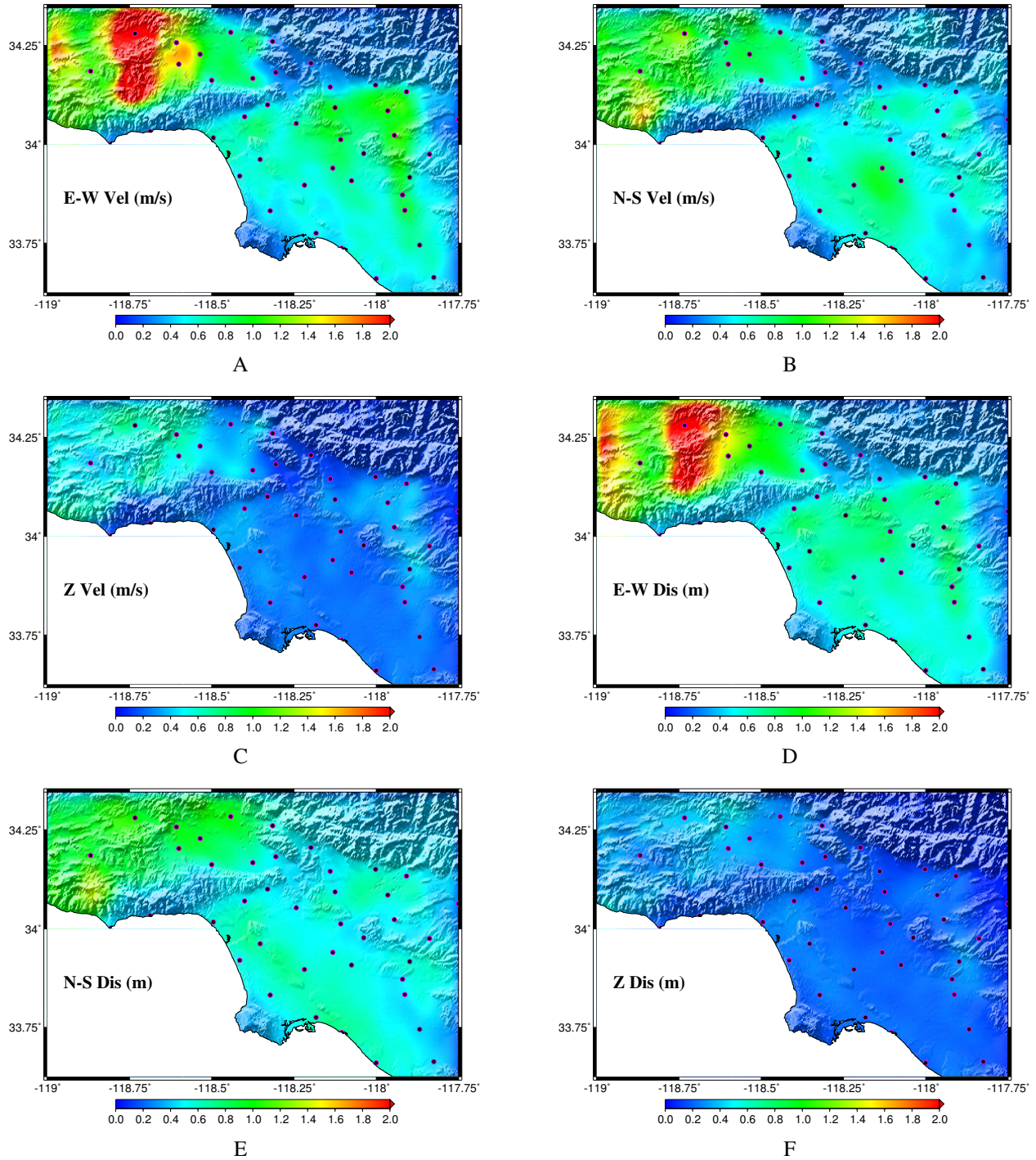


Figure 3: Hypothetical  $M_w 7.9$  earthquake (north-to-south Rupture) on the San Andreas fault – Peak ground motion maps: Shown are the east-west, north-south, and vertical components of the peak ground velocities (A, C, and E, respectively) and displacements (B, D, and F, respectively) of the synthetic seismograms lowpass-filtered with a corner period of 2 s.

(Figure 6). A 6-inch permanent offset at the roof following the Northridge earthquake threw the elevators of the existing building out of alignment requiring building closure and business interrup-

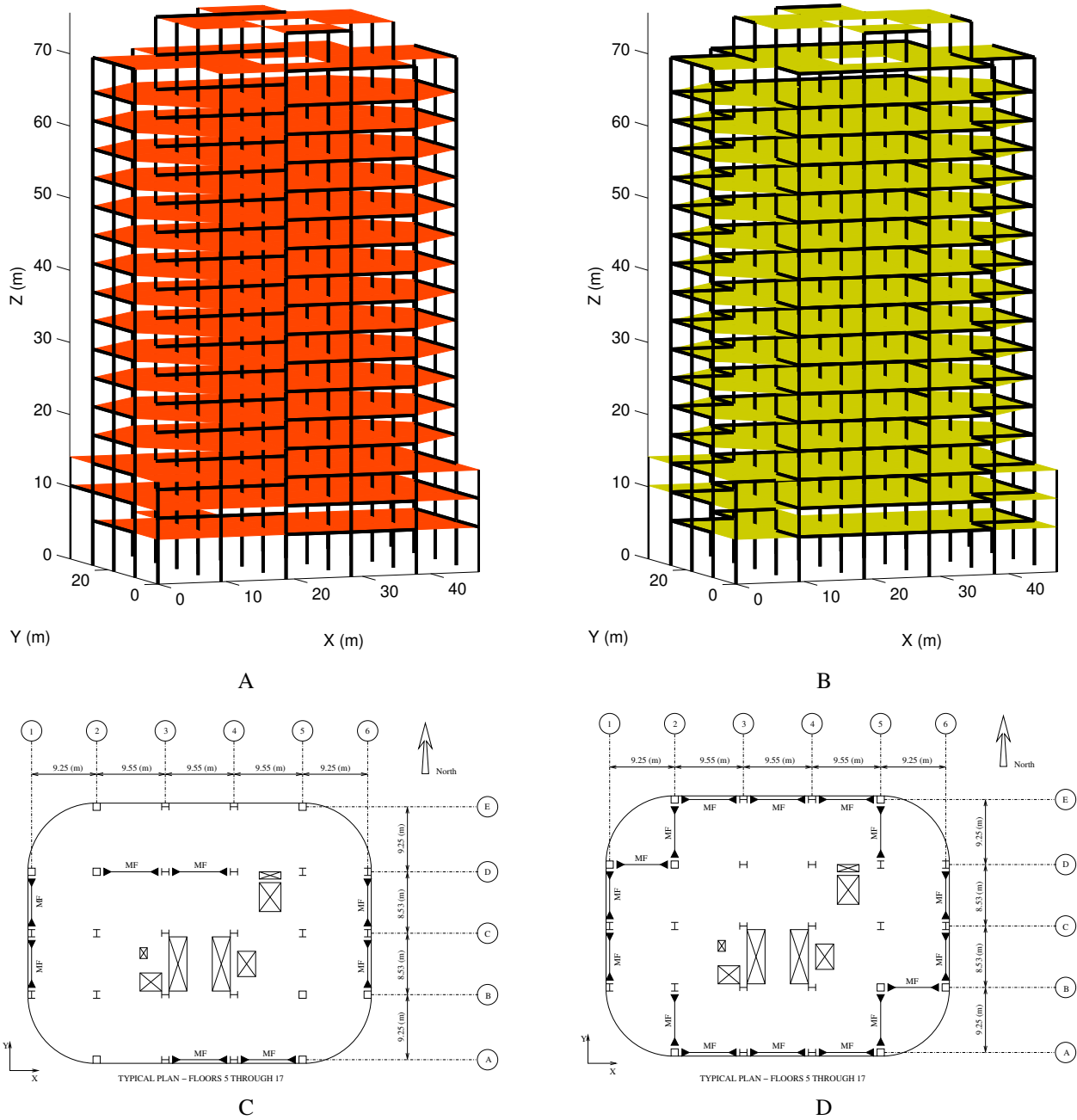


Figure 4: Structural models of the two buildings under study: (A) Isometric view of the existing building (designed using the 1982 Uniform Building Code). (B) Isometric view of the new building (redesigned using the 1997 Uniform Building Code). (C) Plan view of a typical floor of the existing building showing the location of columns and moment-frame (MF) beams. (D) Plan view of a typical floor of the redesigned (new) building showing the location of columns and moment-frame beams. Note the greater number of moment-frame bays in the redesigned building.

tion. In comparison, the tilt in the resigned building is far more prominent. Greater details of the San Andreas earthquake and building response simulations can be found in (Krishnan et al. 2005; Krishnan et al. 2006a; Krishnan et al. 2006b) and online at <http://www.ce.caltech.edu/krishnan>.

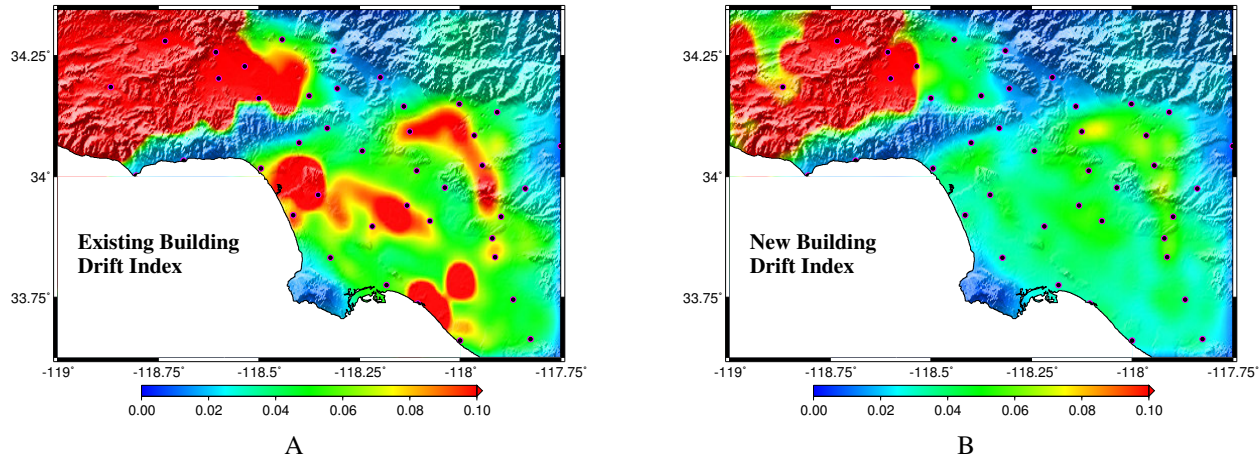


Figure 5: Hypothetical  $M_w 7.9$  earthquake (north-to-south Rupture) on the San Andreas fault – Building performance: Peak interstory drift in the existing and redesigned buildings (A and B, respectively). Peak interstory drifts beyond 0.06 are indicative of severe damage, while drifts below 0.01 are indicative of minimal damage not requiring any significant repair.

This backend example demonstrates the following:

1. We can quantify the effects of natural hazards such as earthquakes by incorporating the underlying science.
2. We can study the impact of a natural disaster numerically, develop strategies to mitigate the damage, and even quantify the impact of our strategies in mitigating damage.
3. We can readily visualize the seismic phenomenon and structure response through visualization tools that have evolved dramatically in the last few years (e.g., see <http://www.ce.caltech.edu/krishnan>).

The backend results are now ready for frontend implementation which includes the following tasks:

1. Upgrade design guidelines.
2. Improve system design.
3. Enforce the upgraded standards.
4. Make the disaster mitigation strategies retro-effective implying make retrofitting mandatory.
5. Ensure construction quality through rigorous mandatory inspection and plan-checks. This is an area that is often not given careful consideration by engineers. Unfortunately, it is one of the areas where there is greater likelihood of serious errors that could jeopardize structural safety.
6. Impose construction zonation so that we do not build in areas with a high hazard level.



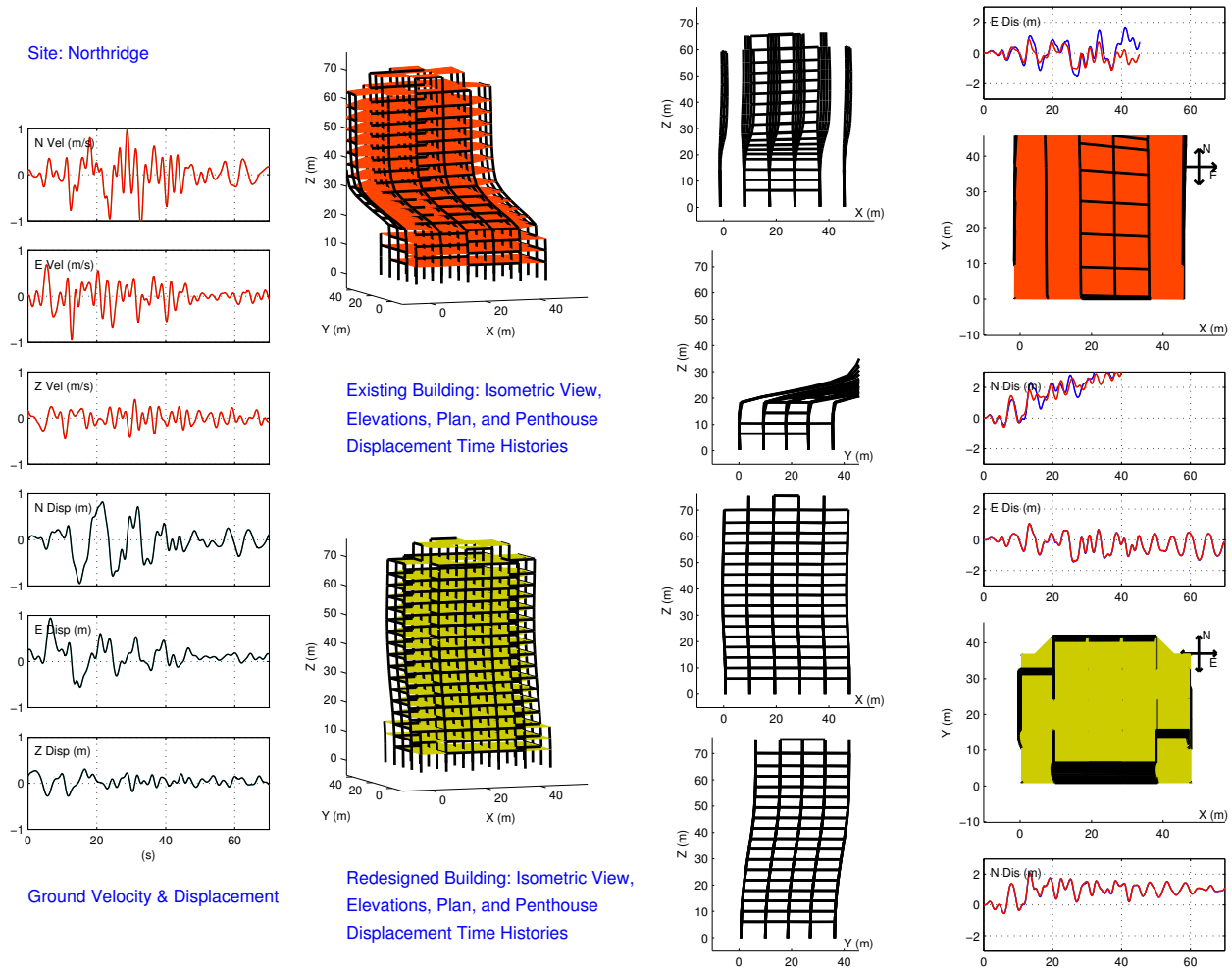


Figure 6: Snapshot of building deformation (scaled up by a factor of 5) immediately following the earthquake at the Northridge analysis site for a hypothetical  $M_w 7.9$  earthquake (south-to-north rupture) on the San Andreas fault. Also shown are the time histories of the three components of the ground velocity and displacement (bandpass-filtered between 2 s and 1000 s using a Butterworth filter), and the east and north components of the penthouse displacement of the existing and redesigned building models.

7. Educate the various stake-holders about the backend findings and implications to gain their support and commitment for frontend implementation.

While these tasks are much easier said than done, there is progress being made thanks to the efforts of dedicated civil engineers the world over. A few success stories are presented in the next section.

## Frontend Implementation – Challenges and Solutions

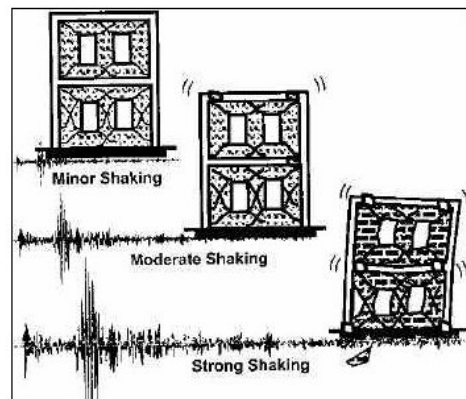
Often, the four primary hurdles to effective frontend implementation are ignorance, poverty, corruption, and lack of political will in governments worldwide. Overcoming these hurdles requires

us to be good communicators and educators. We have to fully utilize mass media to educate the populace. Here is an example of spreading the message through mass media: Professor C.V.R. Murty of the Indian Institute of Technology, Kanpur, India, has authored a series of 24 articles on the basics of earthquake engineering. These articles, sponsored by the Building Materials and Technology Promotion Council, New Delhi, India, have been published in the form of tips in a national daily newspaper, “The Hindu” (Figure 7). Topics range from “causes of earthquakes” to “seismic effects of earthquakes” and “simple measures to improve the performance of masonry and reinforced concrete buildings during earthquakes”. These articles are available online at <http://www.iitk.ac.in/nicee/EQTips>. They are also available in book form at <http://www.nicee.org/Publications.html>.

## THE HINDU

Date:17/04/2003 URL: <http://www.thehindu.com/thehindu/seta/2003/04/17/stories/2003041700150300.htm>

### Quake resistant design, construction



While designing buildings consequences of damage (depending on whether it is a minor, moderate or major quake) have to be kept in view.

SEVERITY OF ground shaking at a given location during an earthquake can be minor, moderate and strong. Relatively speaking, minor shaking occurs frequently, moderate shaking occasionally and strong shaking rarely. For instance, on average annually about 800 earthquakes of magnitude 5.0-5.9 occur in the world while the number is only about 18 for magnitude range 7.0-7.9.

So, should we design and construct a building to resist that rare earthquake shaking that may come once in 500 or 2000 years at the chosen site, even though life of the building may be 50 or 100 years? As it costs a lot to provide extra earthquake safety in buildings, a conflict arises: Should we do away with the design of buildings for earthquake effects? Or should we design buildings to be 'earthquake proof' wherein there is no damage during the strong but rare earthquake shaking?

Figure 7: One of the 24 articles authored by Professor C.V.R. Murty of the Indian Institute of Technology, Kanpur, and published in the national daily newspaper, “The Hindu”.

Illiteracy is a major problem in the developing world. Often, this means we have to take our message directly to the masses. Professor Kerry Sieh of the California Institute of Technology has been doing this on the Indonesian island of Sumatra to warn the largely illiterate populace of rural Sumatra about the dangers of a tsunami and the steps to take in the event of an earthquake. He has created posters not only in English but also in the native Mentawai language giving simple life-saving advice on how to respond to an earthquake or a tsunami (Figure 8).



A



B

Figure 8: Posters in the English and the Mentawai languages created by Professor Kerry Sieh of the California Institute of Technology to educate the rural populace of the Indonesian island of Sumatra about the basics of earthquakes and tsunamis, and actions to be taken when the ground starts shaking.

One of the key reasons for the large number of deaths in extreme events is poverty. Millions of people across the world live in unreinforced adobe houses which are tombs waiting to be enshrined. Unfortunately, the low cost of construction of these houses implies that they will continue to be built even in areas with high seismic risk. So the onus is upon us to develop locally available low-cost earthquake-resistant techniques and materials. For example, a group of Peruvian researchers has developed a simple reinforcing scheme for existing adobe houses in the Andean region that would hopefully give residents sufficient time to escape before collapse occurs in a strong earthquake (Figure 9). This reinforcing scheme successfully implemented in Peru, Bolivia, Colombia, Ecuador, Chile, and Venezuela (<http://www.ceresis.org/project/padobe.htm>).

Too often, even when people could afford modern housing, corruption in the construction industry has resulted in tens of thousands of deaths. The magnitude 7.6, January 26, 2001, Bhuj earthquake in India, and the magnitude 7.4, August 17, 1999, Kocaeli earthquake in Turkey both caused severe devastation in high-end apartment buildings. More than 75 midrise buildings (higher than 10 stories) in Ahmedabad (located about 300 km east of the epicenter) collapsed in the earthquake (Pathak 2001). In Turkey, investigators found rampantly corrupt construction practices, utilizing techniques and materials not suitable in any way to earthquake resistance (Hodgson 2001).

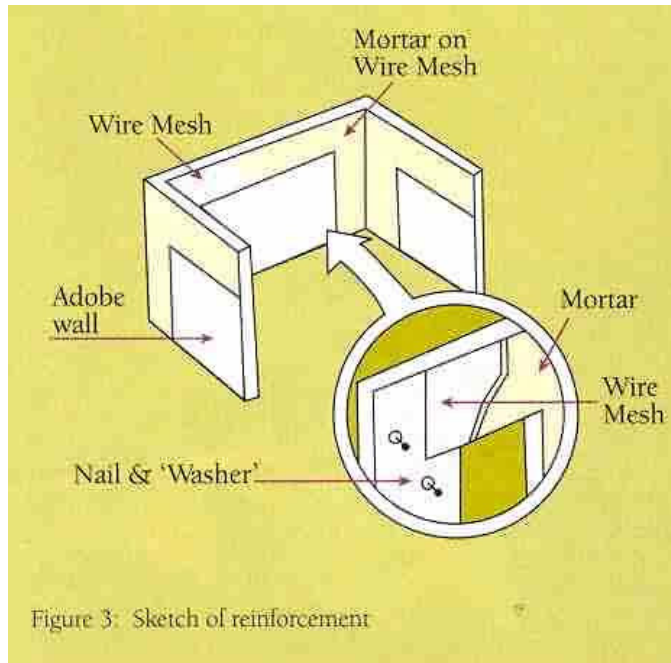


Figure 9: Simple and economical reinforcing scheme for adobe houses proposed by Peruvian researchers and implemented successfully in Peru, Bolivia, Colombia, Ecuador, Chile, and Venezuela (Source: <http://www.ceresis.org/project/padobe.htm>).

These corrupt practices included the use of steel reinforcing bars with less than half the required strength, the use of single hollow brick-wide load-carrying walls, building apartment blocks on swamp land resulting in water seepage into the ground and the basement levels, the use of disproportionate amount of sand in concrete, the use of beach sand mixed with cement to create concrete floors and walls, etc. One investigator even reported finding seashells and domestic refuse mixed into concrete.

The global corruption report for 2005 (<http://www.globalcorruptionreport.org>) focuses specifically on the construction industry and specifies action items for the following eight stakeholder entities: public and private sector clients; construction and engineering companies; international financial institutions, banks, and export credit agencies; trade and professional organizations; auditors; shareholders; government; and civil society organizations. Although engineers form a small fraction of all the stakeholders, it is our responsibility to educate each of the other seven entities in order to establish multiple levels of oversight, making it difficult for corrupt practices to prevail.

Finally, we must constantly engage governments in discussion to ensure that the quality of our infrastructure is maintained. Failure to do so could be catastrophic as was witnessed in New Orleans when the storm surge from hurricane Katrina (August 29, 2005) breached or overtopped the aging levees. Ironically, scientists and engineers at the Louisiana State University hurricane center (<http://www.hurricane.lsu.edu>) had envisioned exactly such a scenario. Just three years earlier (June 23–27, 2002) the local New Orleans daily newspaper, “The Times Picayune”, published a five-part article pointing out the danger to the levees and even identified the most vulnerable regions (Figure 10). In this case the backend effort studies had been conducted, the vulnerability of the infrastructure was identified, and was even publicized through mass media.



Yet, the government cut funding for the city's two main flood control programs including the giant levees almost in half for the year 2005 (Source: Detroit News, September 4, 2005, "Resurrecting New Orleans"). This failure on our part to implement the frontend effectively cost the people of New Orleans dearly. Forcing political commitment to disaster mitigation requires keeping the channels of communication busy with a steady flow of information to educate the decision-makers.

## LAST LINE OF DEFENSE: HOPING THE LEVEES HOLD

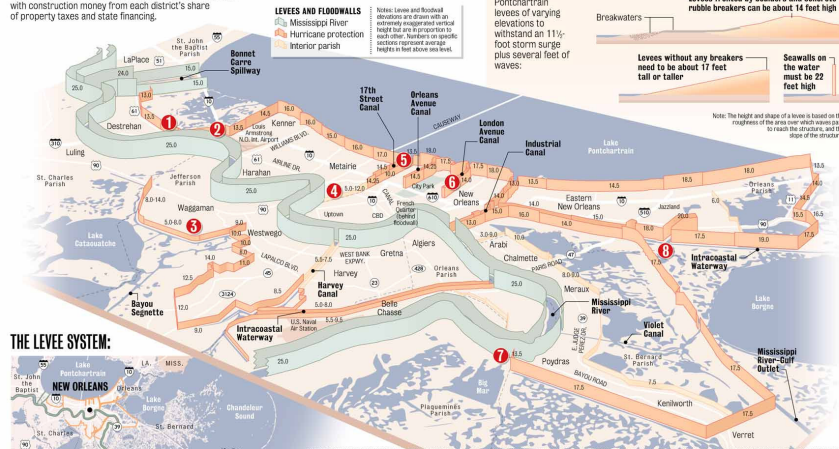
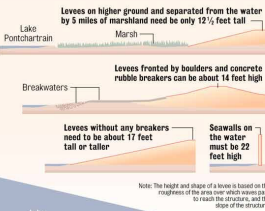
Army Corps of Engineers officials say hurricane levees in the New Orleans area will protect residents from a Category 3 hurricane moving rapidly over the area. But computer models indicate even weaker storms could find chinks in that armor.

### BARRIERS OF EARTH AND CONCRETE

Levees and floodwalls that protect against flooding from both the Mississippi River and hurricanes are built by the Army Corps of Engineers and are maintained by local levee districts. The corps and the local districts share the construction cost of hurricane levees, while the Mississippi River levees are a federal project. Local levee districts also build and maintain nonfederal, lower-elevation levees with construction money from each district's share of property taxes and state financing.

### HEIGHT ISN'T EVERYTHING

Different factors permit Lake Pontchartrain levees of varying elevations to withstand an 11½-foot storm surge plus several feet of waves.

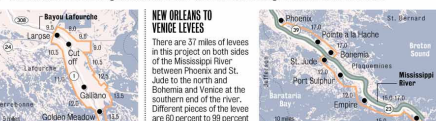


### THE LEVEE SYSTEM:



### FARTHER SOUTH

Residents and businesses in developed areas along bayous and the Mississippi River have successfully argued that the benefits of building levees around their communities outweigh the costs of construction.



### LEVEE HOT SPOTS AROUND NEW ORLEANS:



Figure 10: Five-part article published on June 23–27, 2002, in The Times Picayune daily newspaper highlighting the vulnerability of the levees protecting the city of New Orleans, part of which is below sea level. Source: <http://www.nola.com/hurricane>.

To conclude, if we wish to keep extreme events from becoming catastrophes, we have to become proactive. We have to not only anticipate, estimate, and prepare at the backend, but also ensure that the correct solutions are implemented in a timely manner at the frontend. For this we have to become better communicators and educators, and take a more active role in influencing our



governments.

### **Acknowledgements**

I wish to thank Professor Hiroo Kanamori of the California Institute of Technology and Professor Nasim Uddin of the University of Alabama at Birmingham for reading the manuscript and providing me with valuable comments.

## References

- Agnew, D. C. and K. Sieh (1978). A documentary study of the felt effects of the great California earthquake of 1857. *Bulletin of the Seismological Society of America* 68(6), 1717–1729.
- FEMA (2000). *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*. FEMA-356. Federal Emergency Management Agency, USA.
- Hodgson, B. (January, 2001). Sold a turkey – the great building scandal. *Master Builder* (<http://www.fmb.org.uk/publications/masterbuilder>).
- ICBO (1982). *1982 Uniform Building Code*. Volume 2. International Conference of Building Officials, Whittier, California, USA.
- ICBO (1997). *1997 Uniform Building Code*. Volume 2. International Conference of Building Officials, Whittier, California.
- Kanamori, H. and E. E. Brodsky (2001). The physics of earthquakes. *Physics Today* 54, 34–39.
- Komatitsch, D., Q. Liu, J. Tromp, P. Suss, C. Stidham, and J. H. Shaw (2004). Simulations of ground motion in the Los Angeles basin based upon the spectral-element method. *Bulletin of the Seismological Society of America* 94, 187–206.
- Komatitsch, D. and J. Tromp (1999). Introduction to the spectral-element method for three-dimensional seismic wave propagation. *Geophys. J. Int.* 139, 806–822.
- Krishnan, S. (2003a). FRAME3D – A program for three-dimensional nonlinear time-history analysis of steel buildings: User guide. Technical Report EERL 2003-03, Earthquake Engineering Research Laboratory, California Institute of Technology.
- Krishnan, S. (2003b). Three-dimensional nonlinear analysis of tall irregular steel buildings subject to strong ground motion. Technical Report EERL 2003-01, Earthquake Engineering Research Laboratory, California Institute of Technology, California.
- Krishnan, S. and J. F. Hall (2006a). Modeling steel frame buildings in three dimensions – Part I: Panel zone and plastic hinge beam elements. *Journal of Engineering Mechanics* 132(4), 345–358.
- Krishnan, S. and J. F. Hall (2006b). Modeling steel frame buildings in three dimensions – Part II: Elastofiber beam element and examples. *Journal of Engineering Mechanics* 132(4), 359–374.
- Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2005). Performance of 18-story steel moment-frame buildings during a large San Andreas earthquake – a southern California-wide end-to-end simulation. Technical Report EERL 2005-01, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, California, USA.
- Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2006a). Case studies of damage to tall steel moment-frame buildings in southern California during large San Andreas earthquakes. *Bulletin of the Seismological Society of America* 96(4).
- Krishnan, S., C. Ji, D. Komatitsch, and J. Tromp (2006b). Performance of two 18-story steel moment-frame buildings in southern California during two large simulated San Andreas earthquakes. *Earthquake Spectra* 22(4).

- Liu, Q., J. Polet, D. Komatitsch, and J. Tromp (2004). Spectral-element moment tensor inversions for earthquakes in Southern California. *Bulletin of the Seismological Society of America* 94(5), 1748–1761.
- Meltzner, A. J. and D. J. Wald (1998). Foreshocks and aftershocks of the great 1857 California earthquake. Technical Report USGS Open-File Report 98-465, United States Department of the Interior, USGS, Pasadena, California.
- Pathak, D. N. (March, 2001). Earthquake in Gujarat: Nature's fury, human folly. *PUCL Bulletin*, <http://www.pucl.org/reports/Gujarat/2001/quake1.htm>.
- SAC (1995). Analytical and field investigations of buildings affected by the Northridge earthquake of January 17, 1994 – Part 2. Technical Report SAC 95-04, Part 2, Structural Engineers Association of California, Applied Technology Council, and California Universities for Research in Earthquake Engineering.
- Sieh, K. E. (1977). *A Study of Late Holocene Displacement History Along the South-Central Reach of the San Andreas Fault*. Ph. D. thesis, Stanford University, California.
- Sieh, K. E. (1978a). Pre-historic large earthquakes produced by slip on the San Andreas fault at Pallett creek, California. *Journal of Geophysical Research* 83, 3907–3939.
- Sieh, K. E. (1978b). Slip along the San Andreas fault associated with the great 1857 earthquake. *Bulletin of the Seismological Society of America* 68(5), 1421–1448.
- Sieh, K. E., M. Stuiver, and D. Brillinger (1989). A more precise chronology of earthquakes produced by the San Andreas fault in southern California. *Journal of Geophysical Research* 94, 603–623.
- Weldon, R. J., T. E. Fumal, G. P. Biasi, and K. M. Scharer (2005). Past and future earthquakes on the San Andreas fault. *Science* 308, 966–967.